Analysis of the abstraction of water from freshly mixed jointing mortars in masonry construction

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Abstract

Sharp Front theory is used to derive an equation describing the time taken for a wet mortar joint to be dewatered by an absorbent substrate. The equation shows that the time taken to dewater a mortar joint is directly proportional to its thickness and inversely proportional to the transfer sorptivity, itself a function of the sorptivity of the substrate and the desorptivity of the wet mix. Experimental data are presented which validate this equation and the results show that the time to dewater a mortar depends on both the hydraulicity and the initial water content of the mix. For the practically important case of jointing mortars applied in 10 mm layers to a typical facing brick we show that dewatering times range from 20 seconds to 1 minute for OPC and NHL 2 mortars respectively and that 40-60% of the original mix water is lost in the process.

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1. Introduction

Mortars, plasters and renders are a unique subset of construction materials. They are applied in the freshly mixed wet state as thin layers to absorbent substrates where they are dewatered prior to their transformation from soft to rigid solid. This dewatering has important practical consequences, initially in the adhesion of the mortar to the substrate and later in influencing the strength of the set material. Here we consider the particular case of jointing mortars, typically applied in 10 mm layers to brick, block and stone masonry units. The rate and extent of dewatering depends on the properties of both wet mix and substrate.

We consider a number of parameters here. The desorptivity, R, defines the water retaining ability of a wet mix. The lower the value of R, the more water retaining the mix. The desorptivity is measured using an American Petroleum Institute pressure cell in which water is forced from the wet mix using high pressure nitrogen gas (API 1998; Carter et al. 2003; Green et al. 1999). The desorptivity is defined as the gradient of a plot of the cumulative desorbed volume of water versus the square root of time. The sorptivity, S, defines the ability of a porous material to absorb water by capillarity. The sorptivity is measured (Hall and Hoff 2002; Hall et al. 1986) by placing a dried sample of material in contact with water and removing and weighing the sample at intervals. The sorptivity is defined as the gradient of a plot of the cumulative absorbed volume of water per unit area of absorbing surface versus the square root of time. The transfer sorptivity, A, is a function of both R and S and characterises the ability of a porous material to absorb water from a wet mix (Hall and Hoff 2002). The measurement of transfer sorptivity is identical to that of sorptivity except that the dried substrate material is placed in contact with a wet mix rather than with water. The transfer sorptivity is defined as the gradient of a plot of the cumulative absorbed volume of water per unit area of material in contact with the wet mix versus the square root of time. These parameters are related by (Collier et al. 2007):

$$\frac{1}{A^2} = \frac{1}{R^2} + \frac{1}{S^2}. \qquad [1]$$

Eq. (1), a full derivation of which may be found in (Hall and Hoff 2002), has recently been validated experimentally for the case of clay brick withdrawing water from freshly mixed hydraulic lime and cement mortars (Collier et al. 2007). The purpose of this paper is to apply Sharp Front theory to derive an equation describing the time taken to dewater a wet mix, t_{dw}, by an absorbent substrate and to compare the calculated time with experimental measurements carried out on a range of lime and cement mortars applied to a typical clay brick substrate. This range comprised Portland cement, which is fully cementitious, and two types of natural hydraulic lime NHL 2 and NHL 5. The numerical designation (2 or 5) relates to the nominal strength in MPa and is taken as a measure of cementing action or hydraulicity.

2. Theory

We consider the brick-mortar-brick joint shown schematically in Fig. 1 (a) which represents the idealised case of two bricks simultaneously placed in contact with wet mortar. The bricks are initially dry so that at time $t = 0$ the volume fraction water content of each brick $\theta = 0$. The wet mix, of thickness L, has an initial volume fraction water content θ_i and a volume fraction solids content φ_i so that $\theta + \varphi = 1$. We assume the solids to be uniformly distributed throughout the wet

mix. The bricks withdraw water from the wet mix by capillarity resulting in an advancing wetted zone within each brick. We assume these zones to be of uniform water content, θ_w. As water is drawn through the wet mix into the bricks, solids are transported to the brick-mortar interfaces where they consolidate to form a filter cake which increases in depth as desorption proceeds. Desorption will cease when all the wet mix has been converted to filter cake as shown in Fig. 1 (b). The resulting filter cake will have a lower volume fraction water content, θ_c, and higher volume fraction solids content, φ_c, than the original wet mix. Due to consolidation, the filter cake will be of reduced depth $L_c = L\,\varphi_i/\varphi_c$. At the end of desorption, the total volume of water per unit area desorbed from the wet mix is given by $i = (L\,\theta_i - L_c\,\theta_c)$ and the wet front will have travelled a distance $L_w = i/f$ into each brick where f is the satiated (Wilson et al. 1991) (rather than vacuum saturation) volume fraction porosity of the brick. Since $L_c = L\,\varphi_i/\varphi_c$ and therefore $i = L\,\theta_i - L\,\varphi_i\,\theta_c/\varphi_c$, we say that $i = L(\theta_i - \varphi_i\,\theta_c/\varphi_c) = L\alpha$ where $\alpha = \theta_i - \varphi_i\,\theta_c/\varphi_c$.

We now consider the timescale of the dewatering process. The withdrawal of water from a wet mix by an initially dry (or at least unsaturated) substrate is described by

$$i = At^{1/2} \qquad [2]$$

where A is the transfer sorptivity (Collier et al. 2007). We have already shown that $i = L\alpha$ and so, from Eq. (2), $L\alpha = At^{1/2}$. All the wet mix will be converted to cake at time $t = t_{dw}$ given by

$$t_{dw} = \left(\frac{L\alpha}{A}\right)^2 \qquad [3]$$

and t_{dw} corresponds to the time at which no further water can be abstracted by the substrate.

Eq. (3) shows that t_{dw} increases as the thickness of the mortar bed L increases, and decreases as the transfer sorptivity A increases. The time to dewatering also depends on the volume fractions of water and solids that are in the mix before and after dewatering as described by the reduced variable α. As will be shown later, the parameter α is central to the theoretical predictions of t_{dw} and we reiterate the definition of α here:

$$\alpha = \theta_i - \varphi_i\frac{\theta_c}{\varphi_c} \qquad [4]$$

The dependence of t_{dw} on α is shown in Fig. 2 (which is essentially a plot of Eq. 3) for widely differing values of transfer sorptivity, A, corresponding to a cement mortar of high water content (high A) at one extreme, and a lime mortar of low water content (low A) at the other.

3. Experimental work

To test the above theoretical model and to asses the dewatering characteristics of a range of mortars, experiments were carried out on a clay facing brick (Leicester buff) of high sorptivity (S = 2.5 mm/min$^{1/2}$) as the dewatering substrate. A number of slices cut from one brick were used to determine S and A.

Two sets of freshly mixed mortar were examined: those made with binders of varying hydraulicity (Portland cement, NHL 5 and NHL 2) each with a water:

binder: sand ratio of 0.78:1:2; and NHL 2 mortars made with a range of water: binder ratios 0.78:1, 0.89:1 and 1:1.

3.1 Preparation of mortar mixes

The sand used in all the mixes was the 150 – 300 μm fraction of sieved sand. The mass of both binder and sand required to produce the desired mix proportions by volume were calculated from carefully determined values of density. To ensure consistency, a standard mixing regime was followed. The required volume of water was placed into the bowl of an orbital paddle mixer and the binder material added and mixed for 1 minute. Mixing continually, sand was then added over the following one minute and the resultant mortar mixed for a further minute. The mixing was then halted and all unmixed solids removed from the paddle and the sides of the mixing bowl and incorporated into the mortar. Mixing was then continued giving a total mixing time of 10 minutes. Approximately 1500 g of mortar was prepared in each batch.

3.2 Calculation of the initial volume fraction water and solids content

The initial volume fraction water content of the wet mix is defined by

$$\theta_{\mathrm{i}} = \frac{\text{Volume of water added to mix}}{\text{Volume of wet mix}} \quad . \qquad [5]$$

The mass (and hence the volume) of water contained in the wet mix was known precisely, as was the total mass of wet mix produced. In order to determine the total volume of the wet mix, the following procedure was adopted. A small quantity (75 cm^3) was removed from the mix and placed into a graduated cylinder. The mass of this known volume was measured in order to calculate the density of the mix. Using this value of density, and the measured total mass of the wet mix, the total volume of the wet mix could be calculated.

3.3 Measurement of brick substrate sorptivity

The substrate material used in the experimental work was Leicester buff stock yellow pressed clay facing brick produced by Ibstock Brick Ltd. A full description of the method used to measure the sorptivity S is given in (Hall et al. 1986). In order to eliminate variations in sorptivity across a single brick it was necessary to remove and discard approximately 25 mm from each end face before cutting the remainder of the brick into five equal sections 25 – 30 mm in width. The sections were dried to constant weight at 105ºC in an air oven and the area of the bed face of each section measured. The sorptivity of each section was measured by placing the bed face in contact with a shallow layer of water and removing and weighing at intervals. The sorptivity was determined from the gradient of the graph of the cumulative absorbed volume of water per unit area of absorbing surface versus $t^{1/2}$. The sections were then dried prior to the measurement of transfer sorptivity and t_{dw}.

3.4 Measurement of transfer sorptivity and t_{dw}

The measurement of transfer sorptivity is essentially identical to that of sorptivity except that the substrate material is placed in contact with a wet mortar mix rather than with water (Collier et al. 2007). Although simple in principle, such measurements are experimentally challenging: there is adhesion between the brick

and the wet mix and measurements must be completed before the onset of stiffening and setting. Also, once the brick has been removed from the mortar, hydraulic continuity is lost meaning that the sample cannot be replaced for further measurements. It is for this reason that the absorption of water from a wet mix is carried out using a series of substrate samples, each of which is used only once. The experimental arrangement for the measurement of transfer sorptivity is shown in Fig. 3. Freshly mixed mortar was placed to a depth of 20 mm into each of five equally sized rectangular compartments in a purpose-built mould. One brick section was then placed in contact with the mortar in each compartment. To achieve, as nearly as possible, unidirectional absorption the mould was constructed so that the cross sectional area of each compartment was only slightly larger than the brick slices that were used. The brick sections were removed from the mortar consecutively at increasing time intervals and weighed, after any adhering mortar had been removed with a stiff brush. The mass, and hence the volume, of water absorbed at five time intervals was thus obtained. The experiment was designed, from prior knowledge of the relevant parameters, so that transfer sorptivity, time to dewater and the final water content of the dewatered mix could be obtained from the same set of data as shown later.

3.5 Calculation of final volume fraction water and solids content

The volume fraction water content of the dewatered mix (i.e. the filter cake) is defined by

$$\theta_c = \frac{\text{Volume of water remaining in mix}}{\text{Volume of dewatered mix}} \quad . \qquad [6]$$

For any compartment in the mould, the initial volume of mortar was known. Since θ_i was known, the initial volume of water contained in any compartment could be calculated. When the mortar in that compartment had been dewatered, the mass (and hence the volume) of water absorbed by the corresponding brick section was measured. The volume of water remaining in the mix was then determined by subtracting the volume of water in the brick section from the initial volume of water in the mix contained in that compartment. Following dewatering, the mass of mortar in the compartment was established by subtracting the mass of water abstracted (*i.e*. that contained in the brick slice) from the mass of the original mix. The volume of the dewatered mix was determined by density measurement as described previously. From these measurements, the volume fraction of water in the dewatered mix could be established.

4. Results and Discussion

It should be noted that the experiments, in terms of depth of mortar bed and the timing of the data collection were carefully designed so that both transfer sorptivity and time to dewatering could be obtained from the same set of data without any of the brick samples becoming satiated. Since five was the maximum number of usable samples that could be obtained from one brick, having discarded the end sections, it was only possible to obtain five data points in any one experiment.

4.1 Sorptivity

Values of sorptivity for the ends and five intermediate sections cut from one brick are shown in Fig. 4. These results are typical of Leicester buff bricks and give confidence in the homogeneity of the substrate material. Indeed if such data were plotted for all the bricks used in the experimental work they would superimpose. It should be noted that other types of brick do not exhibit this degree of homogeneity and it is necessary to confirm the uniformity of the substrate material before carrying out the dewatering experiments described here.

4.1.1 Absorption from a wet mix

Fig. 5 shows i vs. $t^{1/2}$ graphs for absorption from cement and NHL mortars prepared with a water: binder ratio of 0.78:1. Fig. 6 shows the same results for a range of NHL 2 mortars of varying water contents. The form of all the graphs is the same: the initial sloping region corresponds to absorption by the substrate, and the horizontal region indicates that no further water is being abstracted from the wet mix.

4.1.2 Transfer sorptivity

The gradient of the sloping region of each graph gives the transfer sorptivity of the mix and these values are summarised in Table 1. Table 1 shows that the transfer sorptivity increases with hydraulicity (or cementing action) and, for a given binder material (in this case NHL 2), that the transfer sorptivity increases as the water: binder ratio increases.

4.1.3 Time to dewater, t_{dw}

The square root of the time to dewater for each mix is obtained from the data in Figs. 5 and 6 by determining the x coordinate of the intersection of the sloping and horizontal regions. It should be noted that each data point in these figures represents a single measurement as described in section 3.4.

Influence of hydraulicity.

From Fig. 5 it can be seen that t_{dw} decreases as hydraulicity increases. This is to be expected because as hydraulicity increases the water releasing ability of the material is enhanced, resulting in an increased desorptivity R and therefore, from Eq. (1), an increased transfer sorptivity A (Table 1). This is confirmed by Eq. (3) which shows that t_{dw} decreases as transfer sorptivity increases.
We explore the influence of hydraulicity further with reference to Table 2 which shows the measured initial and final volume fractions of water, θ_i and θ_c, together with the calculated values of α for each mix. We note in passing that, based on volume fractions, the initial water content of each mix is not the same. This is because of the differences in densities of the binder materials. The density of OPC for example is ~25% greater than that of NHL 2. The values of α in Table 2 show a very weak and non-systematic variation with hydraulicity. From this we can conclude that A, rather than α, is the defining parameter for the time to dewater in this case.

Influence of water content.

Fig. 6 shows that an increase in water: binder ratio is accompanied by an increase in t_{dw}. Clearly θ_i will increase with increasing water: binder ratio and this is shown in Table 2. Increasing the water content of a mix will cause an increase in desorptivity R accompanied by an increase in transfer sorptivity A as shown in last column of Table 1. As is further apparent from Table 2, the higher the initial water content of the mix, the more water can be removed and the lower the final volume fraction water content of the dewatered mix. The large increase in θ_i, together with the large decrease in θ_c, causes a dramatic increase in α (Eq. 4) as the water: binder ratio is increased. We therefore conclude that in the case of varying water: binder ratios, it is α that is the defining parameter in determining t_{dw}.

It is interesting to note at this point the large amount of water that is actually abstracted from these wet mixes – between 40-60%. These values are summarised in Table 2 from which can be seen that the percentage water lost systematically increases with α.

4.2 Confirmation of Eq. (3)

Experimentally measured values of t_{dw} were obtained from the intersections of the lines in Figs. 5 and 6. These are compared with values of t_{dw} calculated from Eq. (3) using the experimentally determined values of A and α from Tables 1 and 2. These results are summarised in Table 3 and show good agreement between the measured and calculated values. The results validate the Sharp Front approach and give confidence that Eq. (3) can be used to estimate the time to dewater 10 mm mortar joints used in practice.

4.3 Time to dewater a 10 mm mortar joint

We now return to the brick-mortar-brick configuration shown in Fig. 1. Having validated Eq. (3), it is now possible to calculate the time to dewater a 10 mm mortar joint for this brick type assuming that each brick is essentially dewatering a 5 mm depth of wet mix (i.e. L = 5 mm). Calculations show that a 10 mm cement mortar bed will be dewatered in ~20 seconds and NHL 2 mortar bed in ~1 minute for the particular brick considered here.

5. Conclusions

Sharp Front theory has been shown to provide a satisfactory model to describe the dewatering of a mortar layer of thickness L by a masonry substrate through the equation $t_{dw} = (L\alpha/A)^2$ where A is the transfer sorptivity and α a variable that embodies the initial and final volume fraction water and solid contents of the mortar.

The results show that times to dewater decrease with increasing mortar hydraulicity, and in these experiments the transfer sorptivity A was the controlling parameter. The influence of water content was shown to be defined by changes in α. This variable is particularly sensitive to changes in initial and final volume fraction water contents. Higher water content mixes have longer dewatering times and lower final water contents.

Calculations for the dewatering of a standard 10 mm joint between masonry units indicate dewatering times of 20 s for a Portland cement mortar and 60 s for NHL 2. Approximately 40-60% of the original mix water is lost by dewatering.
Taken together, the results have important consequences for construction practice since dewatering will affect both interfacial bonding and the properties of the final set mix.

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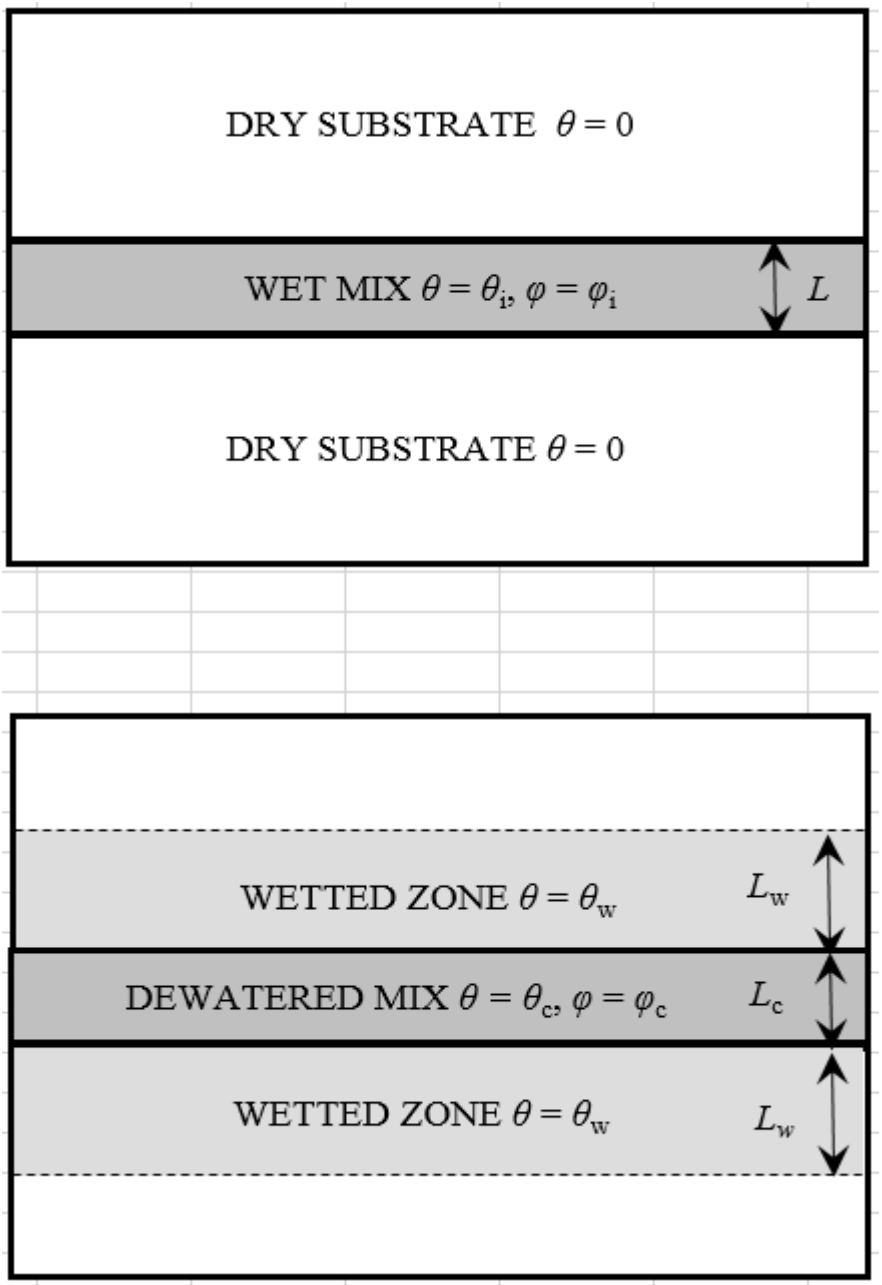

Figure 1. Schematic representation of the dewatering of a fresh mortar joint in brickwork: (a) immediately prior to dewatering; (b) on completion of dewatering at t = t_{dw}.

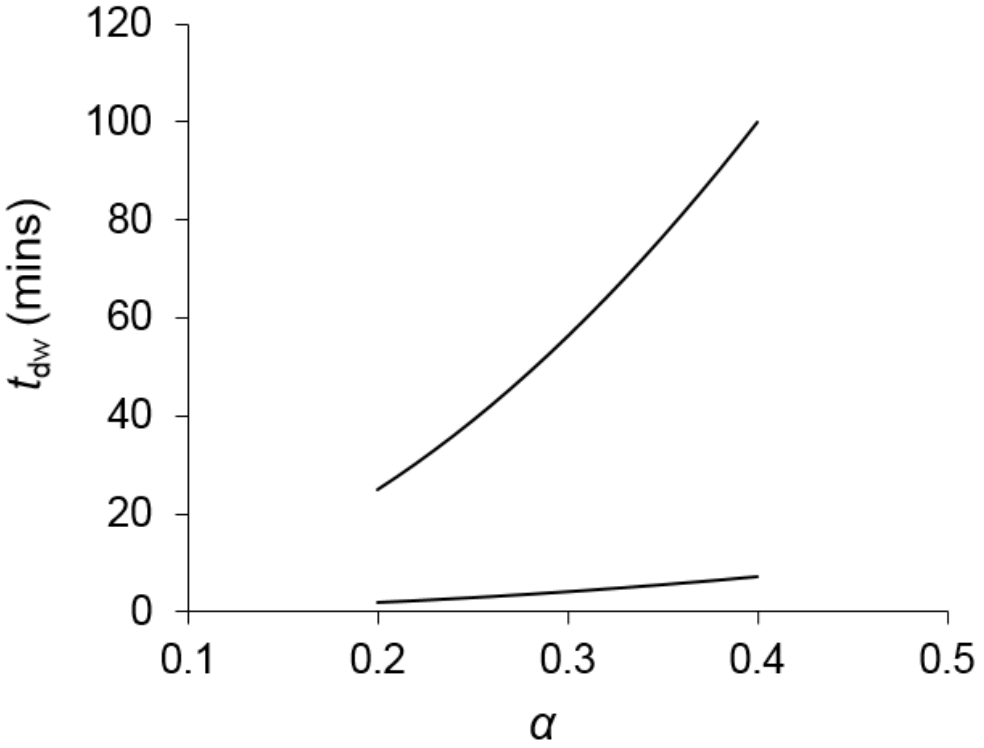

Figure 2. Theoretical plots of Eq. (3) for a high transfer sorptivity (A = 3 mm/min$^{1/2}$, lower line) and a low transfer sorptivity (A = 0.8 mm/min$^{1/2}$, upper line). t_{dw} calculated using L = 20 mm with α in the range 0.2 to 0.4 in each case.

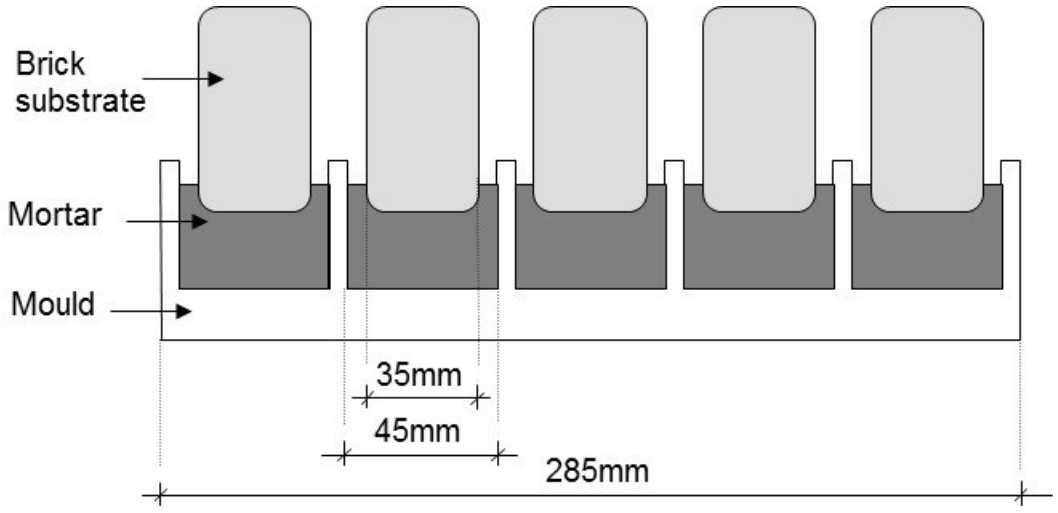

Figure 3. Experimental arrangement for the measurement of transfer sorptivity and time to dewatering.

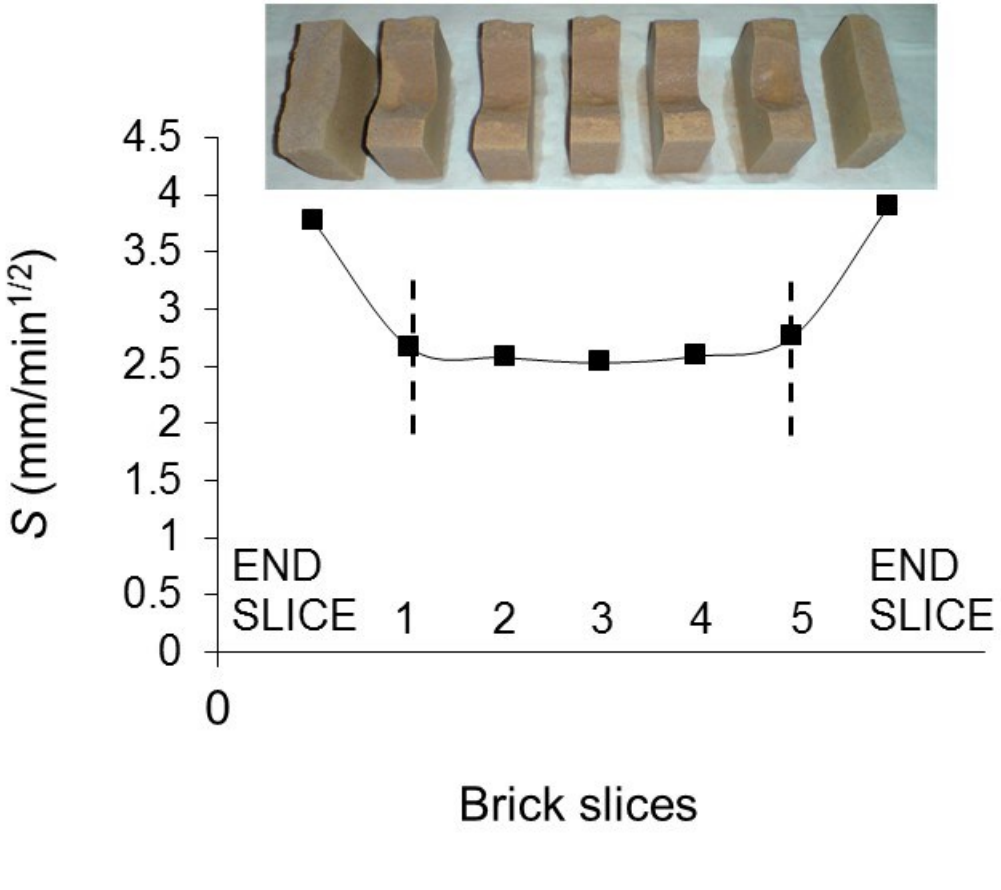

Figure 4. Measured values of sorptivity carried out on sections cut from a single clay brick.

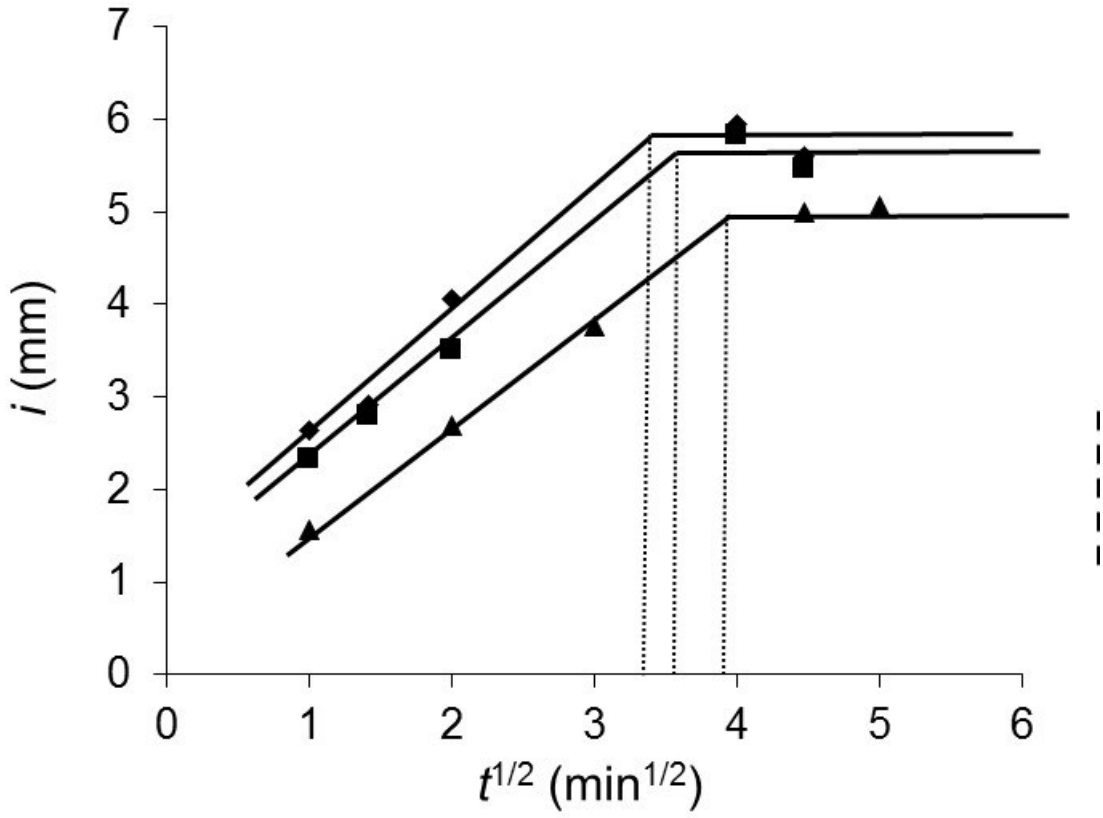

Figure 5. Water absorbed by a brick substrate from a range of wet mixes of varying hydraulicity: cumulative absorbed volume per unit area i versus $t^{1/2}$ for ▲, NHL 2; ■, NHL 5; and ♦, OPC mortars all of mix composition water: binder: sand 0.78:1:2 by volume.

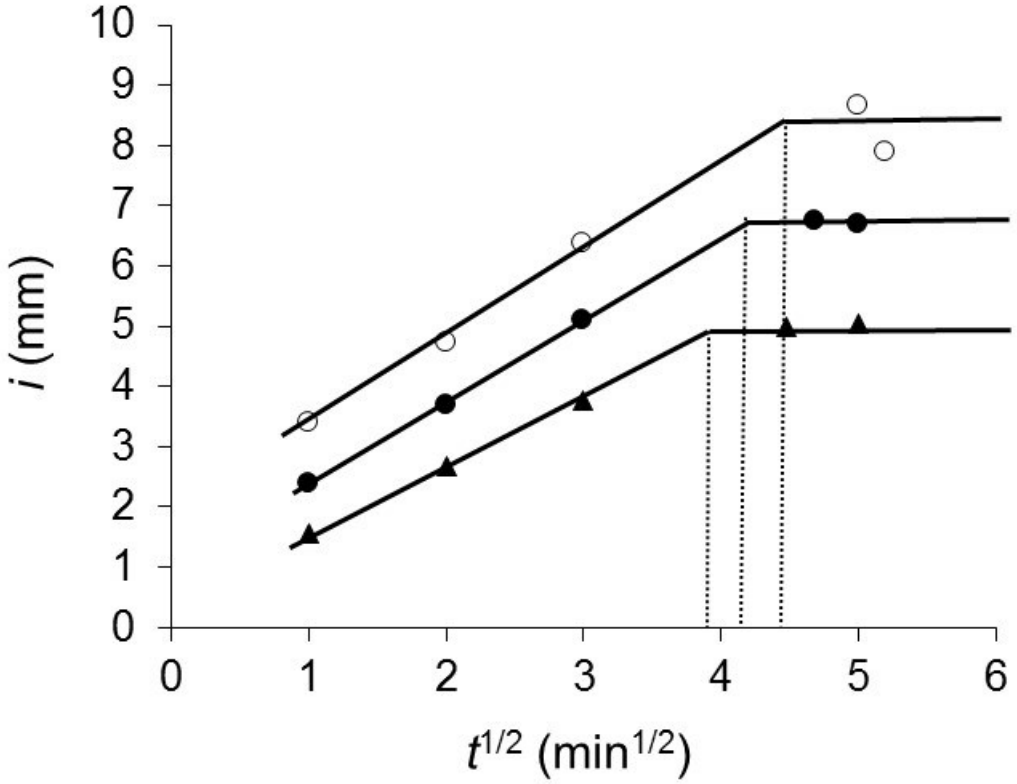

Figure 6. Water absorbed by a brick substrate from a range of wet mixes of varying water content: cumulative absorbed volume per unit area i versus $t^{1/2}$ for NHL 2 mortars of binder: sand ratio 1:2 with water: binder ratios ▲, 0.78:1; ●, 0.89:1; and ○, 1:1.

Tables

Binder	Water:binder ratio	Transfer sorptivity ($mm/min^{1/2}$)
NHL 2	0.78:1	0.987
NHL 5	0.78:1	0.992
OPC	0.78:1	1.256
NHL 2	0.78:1	0.987
NHL 2	0.89:1	1.183
NHL 2	1:1	0.987

Table 1.Directly measured values of transfer sorptivity, A, for the range of mortars examined.

Binder	Water:binder ratio	ρ (g/cm3) of fresh mix	θ_i	θ_c	α	% water loss
NHL 2	0.78:1	2.020	0.355	0.209	0.19	37.97
NHL 5	0.78:1	2.153	0.364	0.234	0.17	35.60
OPC	0.78:1	2.559	0.411	0.255	0.21	41.17
NHL 2	0.78:1	2.020	0.355	0.209	0.19	41.17
NHL 2	0.89:1	1.978	0.387	0.199	0.24	45.75
NHL 2	1:1	1.923	0.413	0.175	0.29	57.18

Table 2. Data defining the properties of the mortars before and after dewatering.

Binder	Water:binder ratio	t_{dw} (min) (MEASURED)	t_{dw} (min) (CALCULATED)
NHL 2	0.78:1	15.5	14.1
NHL 5	0.78:1	12.2	11.6
OPC	0.78:1	10.7	11.2
NHL 2	0.78:1	15.5	14.1
NHL 2	0.89:1	16.7	15.8
NHL 2	1:1	19.3	19.0

Table 3. Directly measured values of t_{dw} compared to those calculated from Eq. (3).